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NEUTRAL CURRENTS - THE STRUCTURE OF THE COUPLING*

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I report here on latest results from an investigation of the form of the neutral current coupling in the inclusive channels

$$\nu_\mu + N \rightarrow \nu_\mu + \text{hadrons}$$

and

$$\bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + \text{hadrons}.$$

The experiment was conducted by the Caltech-Fermilab group in October 1974, by the following people: F. Merritt, B. Barish, J. F. Bartlett, K. W. Brown, A. Bodek, D. Buchholz, E. Fisk, G. Krafczyk, F. Jacquet, F. Sciulli, H. Suter, and L. Stutte.

The data were taken in the Fermilab narrow band beam set to a mean secondary hadron energy of ± 170 GeV. The distributions of total energy, observed in the target calorimeter, for charged current events in which the muon momentum was measured, shown in figure 1, reflect the dichromatic structure of the beam, with average energies for neutrinos from pion and kaon decay of 50 and 150 GeV, respectively.

The two main sources of background present in the data sample come from cosmic ray interactions, and from neutrinos (and anti-neutrinos) which are produced by decays before momentum and sign selection has occurred (wide-band background). Both backgrounds are measured and empirically subtracted from the data. The first (cosmic rays) is measured in an off-beam gate. The second (wide-band) is measured by closing a slit at the entrance to the decay pipe. Thus, our data sample contains beam associated neutrinos (or anti-neutrinos) with little or no contamination from the neutrino of opposite helicity.

Figure 2 shows an example of a neutral current candidate from this run. The event occurs well inside the Fe calorimeter; significant hadron energy is deposited, however, no visible muon is observed.

The data sample was separated into neutral - (NC) and charged - (CC) current events on the basis of penetration (Fig. 3). Muons were identified if they penetrated more than 1.6 meters of iron. This does not, however, produce a clean sample of NC events - some fraction of the charged current events will have a muon emitted at such a wide angle that it will not be observed. Fig. 3 shows a rough estimate for this contamination using a simple charged current model. The excess number of events above the dashed curve is interpreted as the neutral current signal and is a "Raw" level of excess:

$$R_{\nu} = 0.241 \pm 0.034$$

$$R_{\bar{\nu}} = 0.35 \pm 0.11$$

where the errors are statistical only. This level is called "raw" since a minimum hadron energy (E_H) for NC events (see Fig. 4) is required by the trigger. This trigger only reaches full efficiency for $E_H \sim 12$ GeV and thus only data with $E_H \geqslant 12$ GeV has been analyzed. To know the actual $\sigma_{NC} / \sigma_{CC}$ requires an extrapolation to $E_H = 0$ and thus a knowledge of the NC y-distributions.

We have chosen to directly analyze our neutral current data to obtain the couplings by fitting the NC hadron energy distributions (Fig. 5) to the functional form

$$\frac{dN^2}{dy} = \frac{G^2 M E_{\nu}}{\pi} F_{\nu} \left[g_N + g_P (1-y)^2 + g_F y^2 \right]$$

and

$$\frac{dN^{\bar{\nu}}}{dy} = \frac{G^2 M E_{\bar{\nu}}}{\pi} F_{\bar{\nu}} \left[g_P + g_N (1-y)^2 + g_F y^2 \right]$$

where F_{ν}, $F_{\bar{\nu}}$ represent the flux of neutrinos and anti-neutrinos, respectively, E_{ν} ($E_{\bar{\nu}}$) is the energy of the incoming neutrino (anti-neutrino) and $y = E_H / E_{\nu}$, the usual scaling variable. g_N, g_P and g_F represent the coefficients of negative helicity, positive helicity and spin-flip. For this paper, I will assume $g_F \equiv 0$.

The parameter g_N contains contributions from V-A neutrino-quark scattering and V-A neutrino-anti-quark scattering. (Note: for a pure vector (or pure axial) interaction, $g_N \equiv g_P$, independent of the quark, anti-quark composition of the nucleus).

Two pieces of information are required in order to perform this two parameter fit:

1) The value of the fluxes F_ν, $F_{\bar{\nu}}$. (The short beam spill, ~1msec, did not allow us to measure them directly.)

2) The number of the CC events which still remain as contamination in the NC sample. (These are events with large muon angle and therefore large y.)

We have used the charged current data, fit to three radically different models, discussed below, to obtain the required information. As will be seen from the results of the fits, the structure of the NC couplings is largely insensitive to the assumptions made about the charged currents. The estimates for the fluxes, F_ν and $F_{\bar{\nu}}$, were obtained in two ways: 1) fitting the models to all the CC data and 2) using just the small y CC data where our detection efficiency is quite high. The value of $\frac{dN}{dy}$ at $y = 0$ for CC events is just $\frac{G^2ME_\nu}{\pi} F_\nu$, if charge symmetry is correct.

In practice, of course, an extrapolation from small y ($y<0.2$) to $y = 0$ must be done using the models. However, since the statistical error on these data is quite large, the details of the models matter very little.

The three charged current models used were:

1) the Scaling Model

$$\nu: \quad \frac{dC^\nu}{dxdy} = \frac{G^2ME_\nu}{\pi} F_\nu \left\{ q(x) + \bar{q}(x)(1-y)^2 \right\}$$

$$\bar{\nu}: \quad \frac{dC^{\bar{\nu}}}{dxdy} = \frac{G^2ME_{\bar{\nu}}}{\pi} F_{\bar{\nu}} \left\{ q(x)\ (1-y)^2 + \bar{q}(x) \right\}$$

where
$$q(x) + \bar{q}(x) = F_2^{ed}(x)$$
$$\bar{q}(x) = \frac{F_2^{ed}(x)}{2}\ e^{-\lambda x}$$

($F_2^{ed}(x)$ is the structure function measured by SLAC-MIT with electrons on deuterium.[1]) In terms of the quark-parton model, $q(x)$ ($\bar{q}(x)$) is just the fraction of the nucleon's momentum carried by quarks (antiquarks). All ignorance about charged current behavior is lumped into one parameter for this fit $\alpha = \frac{\bar{Q}}{Q+\bar{Q}}$

where $Q = \int_0^1 q(x)\ dx,\ \bar{Q} = \int_0^1 \bar{q}(x)\ dx$.

2) Non-Scaling Model

This has the same functional form as the above but now α is a function of energy. There are two parameters here (α_1 for neutrinos from π-decay, $\langle E_\nu \rangle$ ~50 GeV, and α_2 for neutrinos from K-decay, $\langle E_\nu \rangle$ ~150 GeV).

3) Non-scaling model with right-handed currents and the production of a new heavy quark.[2] For this fit we assume α = 0.06 (the best fit from low energy neutrino data) and fit the data for the mass of the new quark (M_B).

The results of the fit for g_N and g_P (quoted here as the equivalents $g = g_N + g_P$ and $P = g_P / g$) for each of the charged current models, are given in Table 1, which presents values for each of the two methods of obtaining the fluxes. As stated earlier, g and P are relatively insensitive to any assumptions about the charged currents.

Figure 6a shows two parameter contours (statistical errors only) for the best estimate of g_N and g_P. Including systematic errors these best estimates are

$$g_N = (0.199 \pm 0.023) \pm 0.02$$

$$g_P = (0.110 \pm 0.037) \pm 0.02$$

where statistical errors are given inside the parentheses and estimated systematic errors outside. Figure 6b shows the contours again with lines of V-A, V+A and the prediction of the Weinberg-Salam model[3] for the assumption that α = 0.17 for CC events.

Since g_N includes a mixture of V-A neutrino-quark and V+A neutrino-anti-quark scattering, (and g_P contains V-A neutrino-anti-quark and V+A neutrino-quark scattering) we are only measuring the strength and fraction of negative and positive helicity coupling in the neutral current data. To separate the V-a (g-) and V+A (g+) contributions we can re-express g_N and g_P as follows:

$$g_N = (1-\alpha_{nc})\, g- \; + \alpha_{nc}\, g+$$

$$g_P = \alpha_{nc}\, g- \; + (1-\alpha_{nc})\, g+$$

where α_{nc} is the integrated fraction of momentum carried by the anti-quarks in the nucleon for the neutral current interactions, a number which to date has not been measured. Figure 7 shows the contours for g - and g + for two different values of α_{nc}, $\alpha_{nc} = 0.06$ and $\alpha_{nc} = 0.17$ (the best fit at $E_\nu \sim 50$ GeV).

It can be seen from these two contours that the results are reasonably insensitive to the value assumed for α_{nc}. The data are inconsistent with a pure V + A interaction, and lie somewhere in between V (or A) and V-A. The fit lies about 1-1/2 standard deviations from pure V (or A), and about 1 to 1.7 standard deviations from pure V-A, depending on the value for α_{nc}. Both in strength and magnitude, the data are quite consistent with the predictions of the Weinberg-Salam model(3) giving a best value for the V,A mixing angle of

$$\sin^2\theta_\omega = 0.331 \begin{smallmatrix} + 0.056 \\ - 0.049 \end{smallmatrix}$$

for $\alpha_{nc} = 0.17$.

References

1. A. Bodek, Ph.D. Thesis, Massachusetts Institute of Technology, Report No. COO-3069-116, 1973, (unpublished).

2. R. Michael Bernett, Harvard Preprint (1975).

3. S. Weinberg, Phys. Rev. Lett., 19, (1967) and 27, 1683, (1972). A. Salam and J. C. Ward, Phys. Lett., 13, 168 (1964).

TABLE I:

			Neutral Current Result		
CC Model	Ignorance Parameter	χ^2_{cc}	$g = g_n + g_p$	$P = g_p / g$	Norm. $(F, \bar{F})$
Scaling $\alpha =$	(0.14 to 0.35) 0.29	18.6	$.30 \pm .03$	$.36 \pm .09$	Model
			$.32 \pm .04$	$.37 \pm .10$	Small y
Non-Scaling (50GeV) $\alpha_\pi =$	0.17 (0.06 to 0.30)	15.8	$.30 \pm .03$	$.39 \pm .09$	Model
(150GeV) $\alpha_k =$	0.32 ($>$0.17)		$.32 \pm .04$	$.41 \pm .10$	Small y
B - Quark $\alpha = .06$		20.	$.32 \pm .04$	$.33 \pm .09$	Model
$M_B =$	(3.3 to 6.3) 5 GeV		$.31 \pm .04$	$.41 \pm .10$	Small y

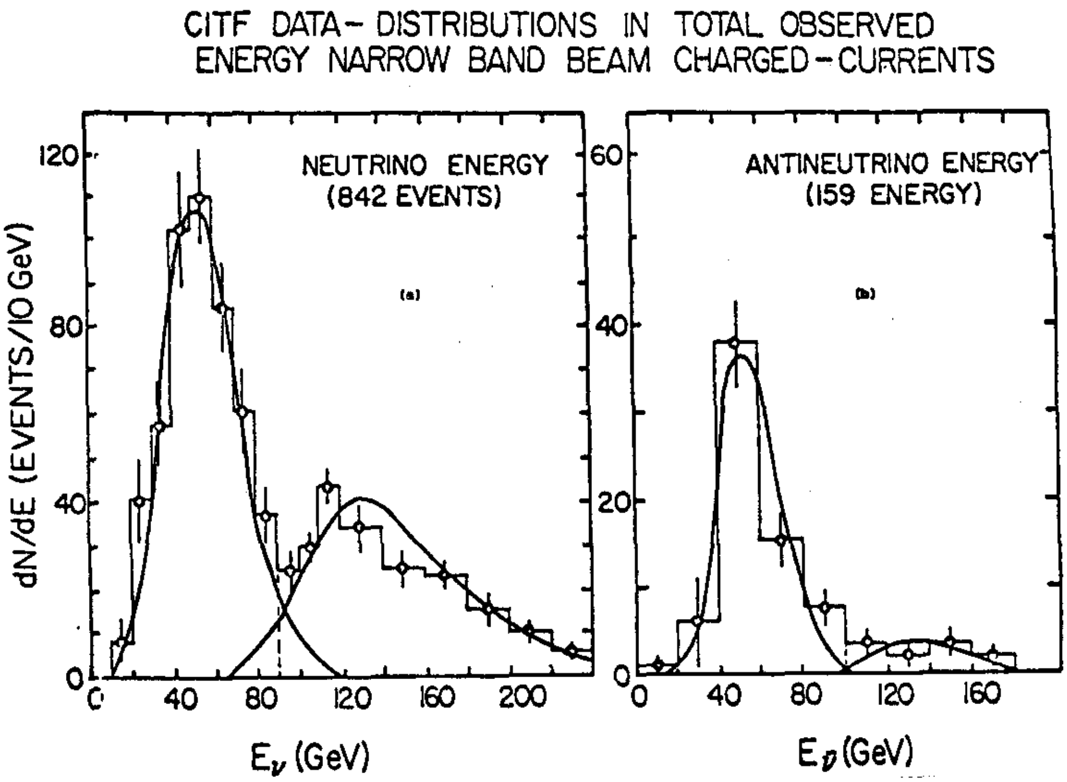
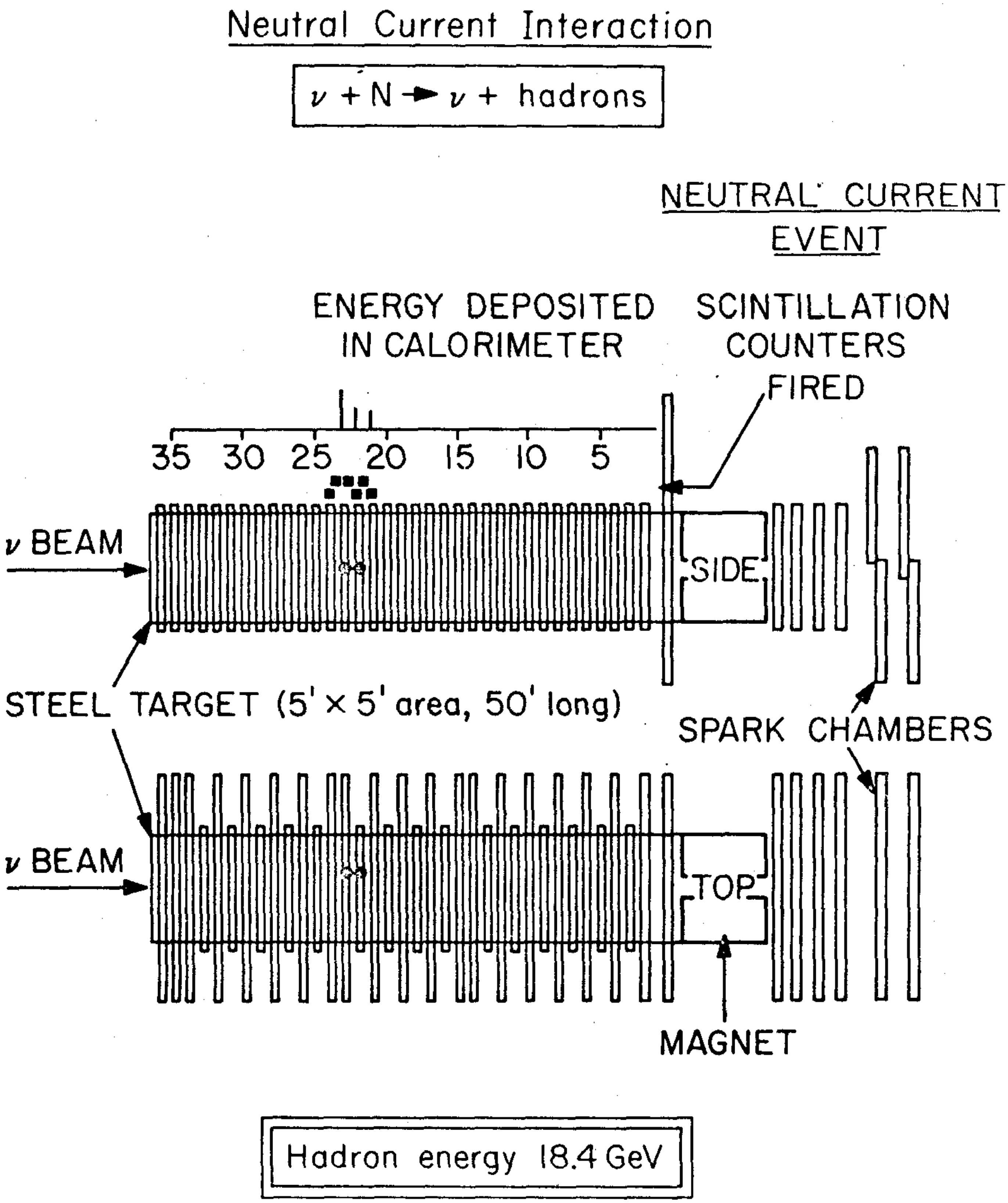


FIG. 1

Total Energy observed in Calorimeter for Charged Current Events.

FIG. 2

Neutral Current Candidate



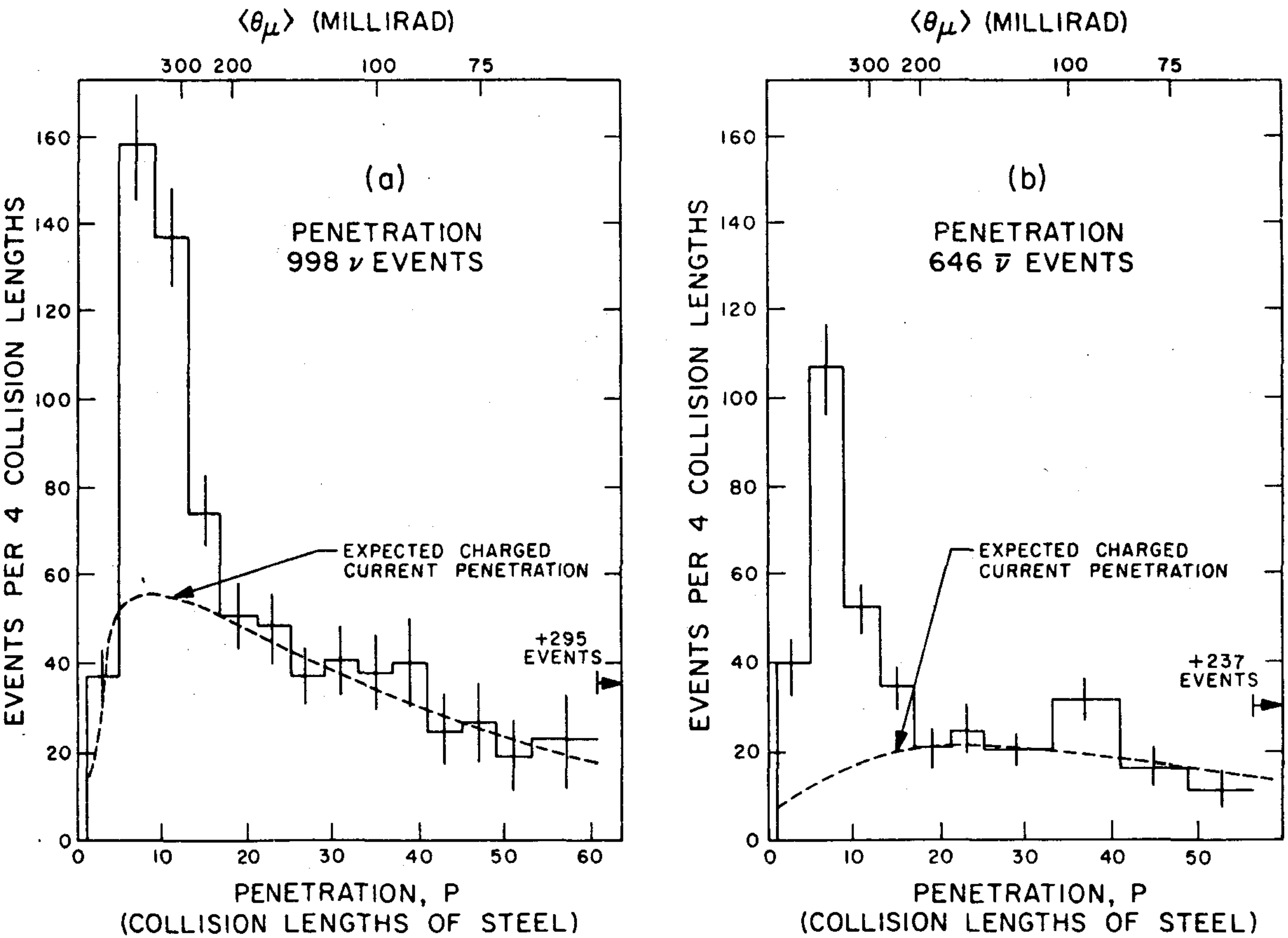


FIG. 3

Penetration curves for the most penetrating particle in neutrino and anti-neutrino collisions.

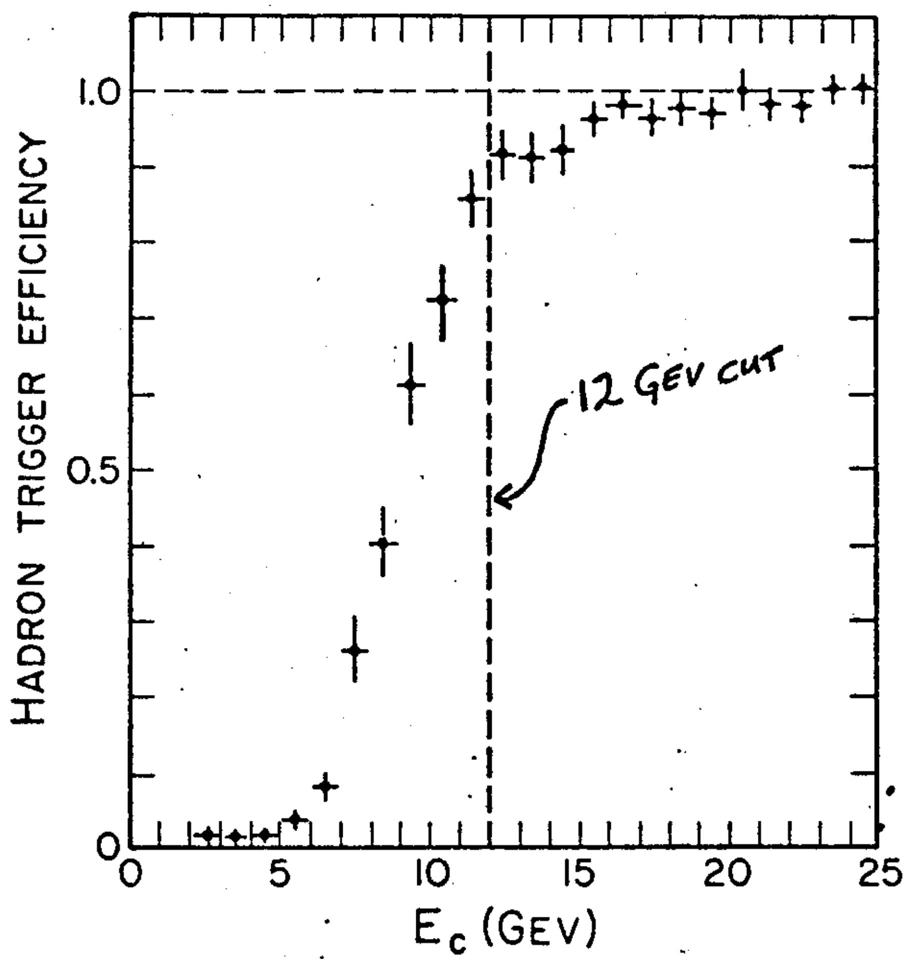


FIG. 4

Hadron Trigger Efficiency

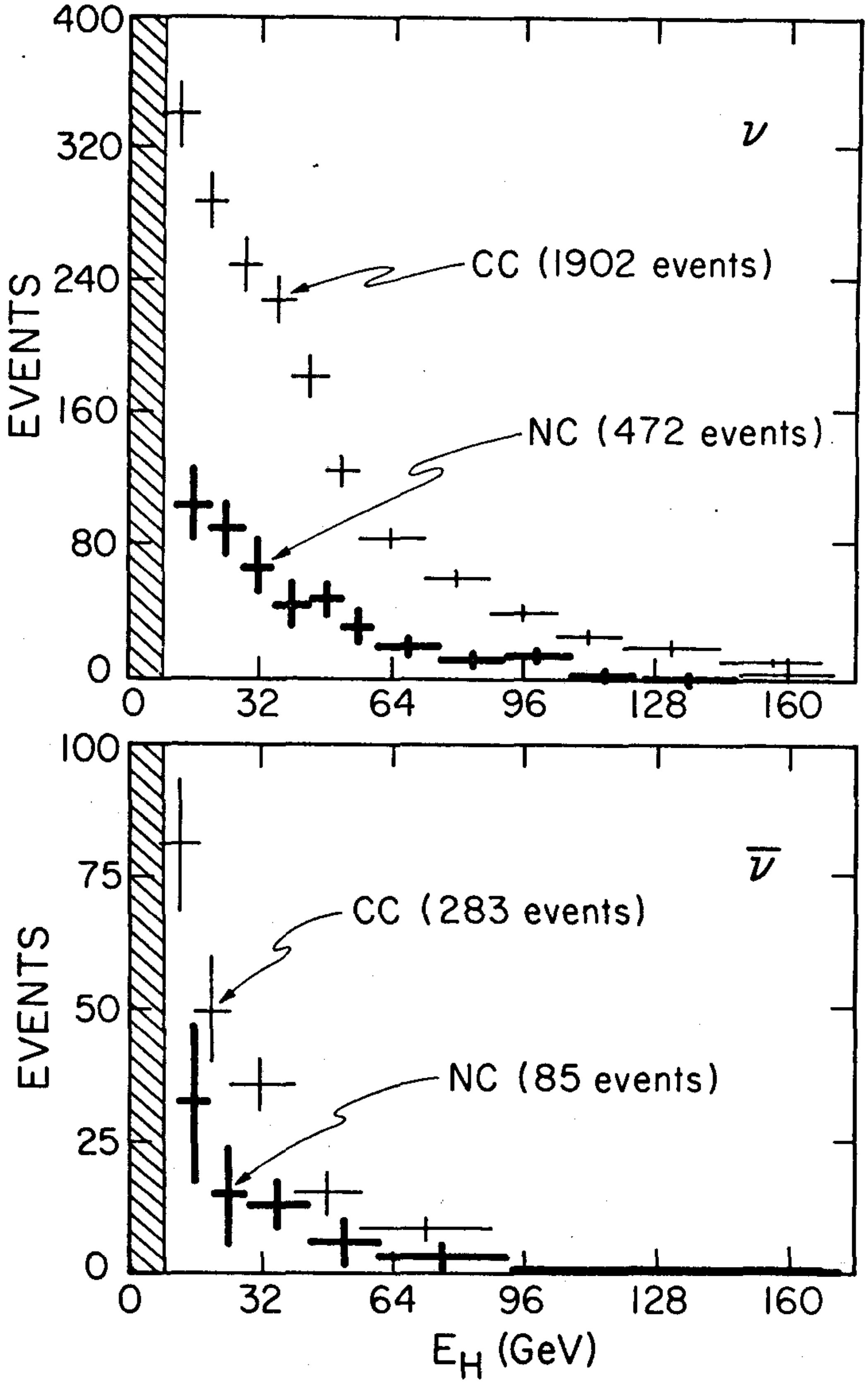


FIG. 5

Charged and Neutral Current Distributions for Neutrinos and Anti-Neutrinos with $E_H > 12$ GeV.

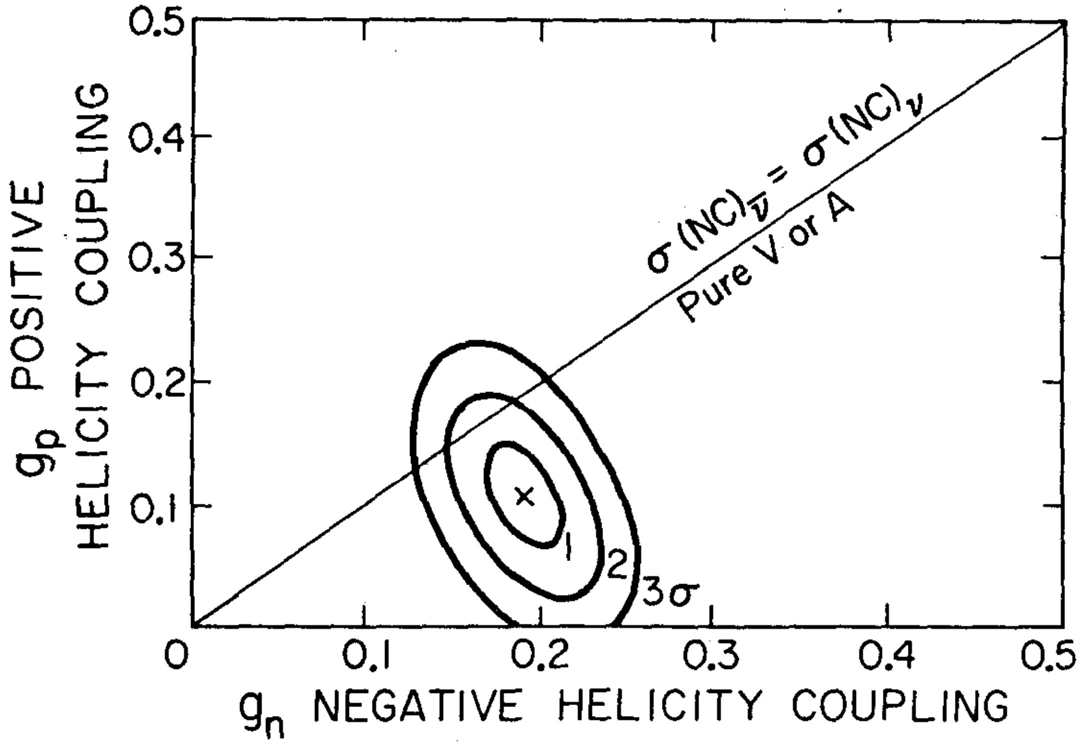


FIG. 6a

Two Parameter Contours for the Best Fit for the Negative and Positive Helicity Coupling for Neutral Currents.

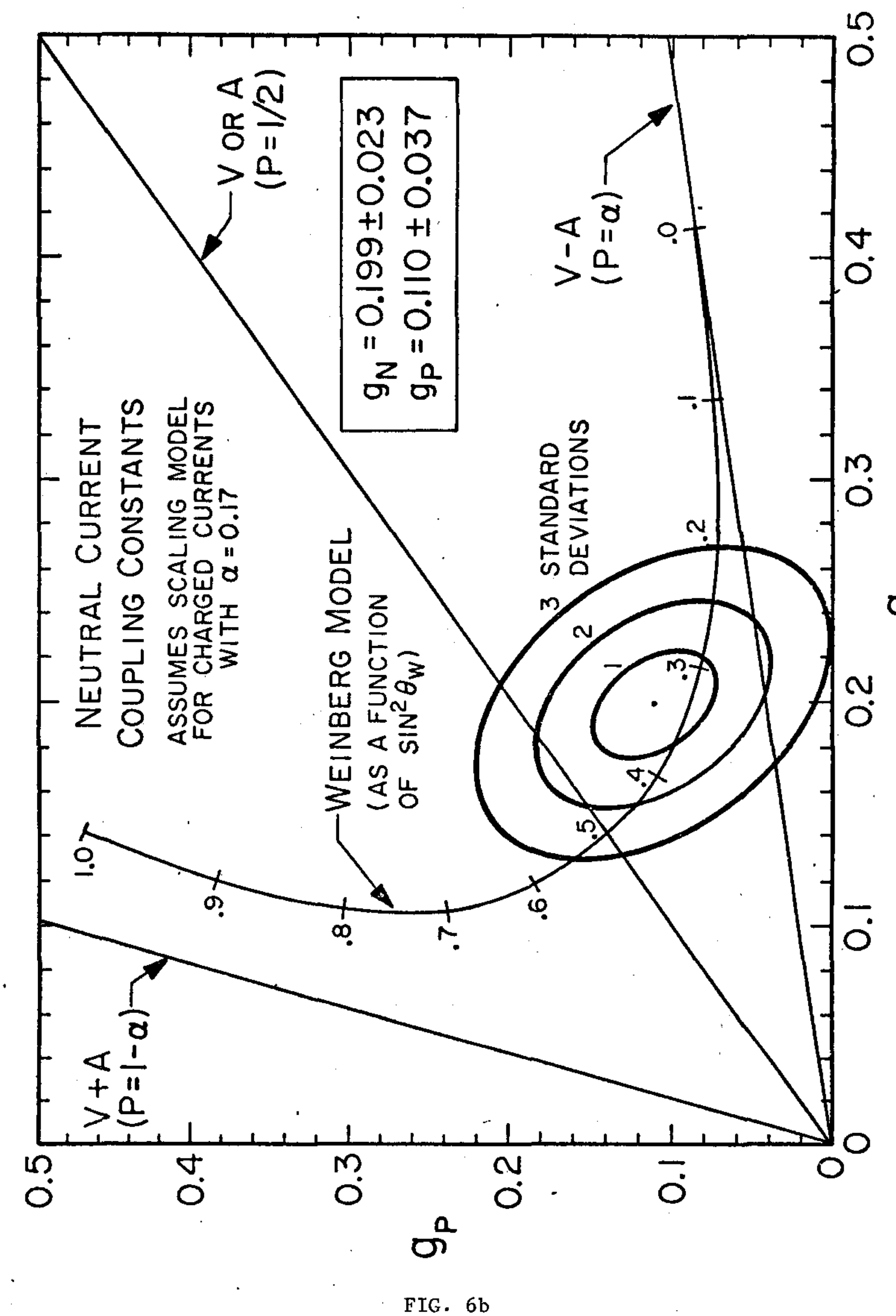


FIG. 6b

Two Parameter Contours, as in Fig. 6a, with Predictions of V-A, V + A and Weinberg Model for Charged Current $\alpha = 0.17$.

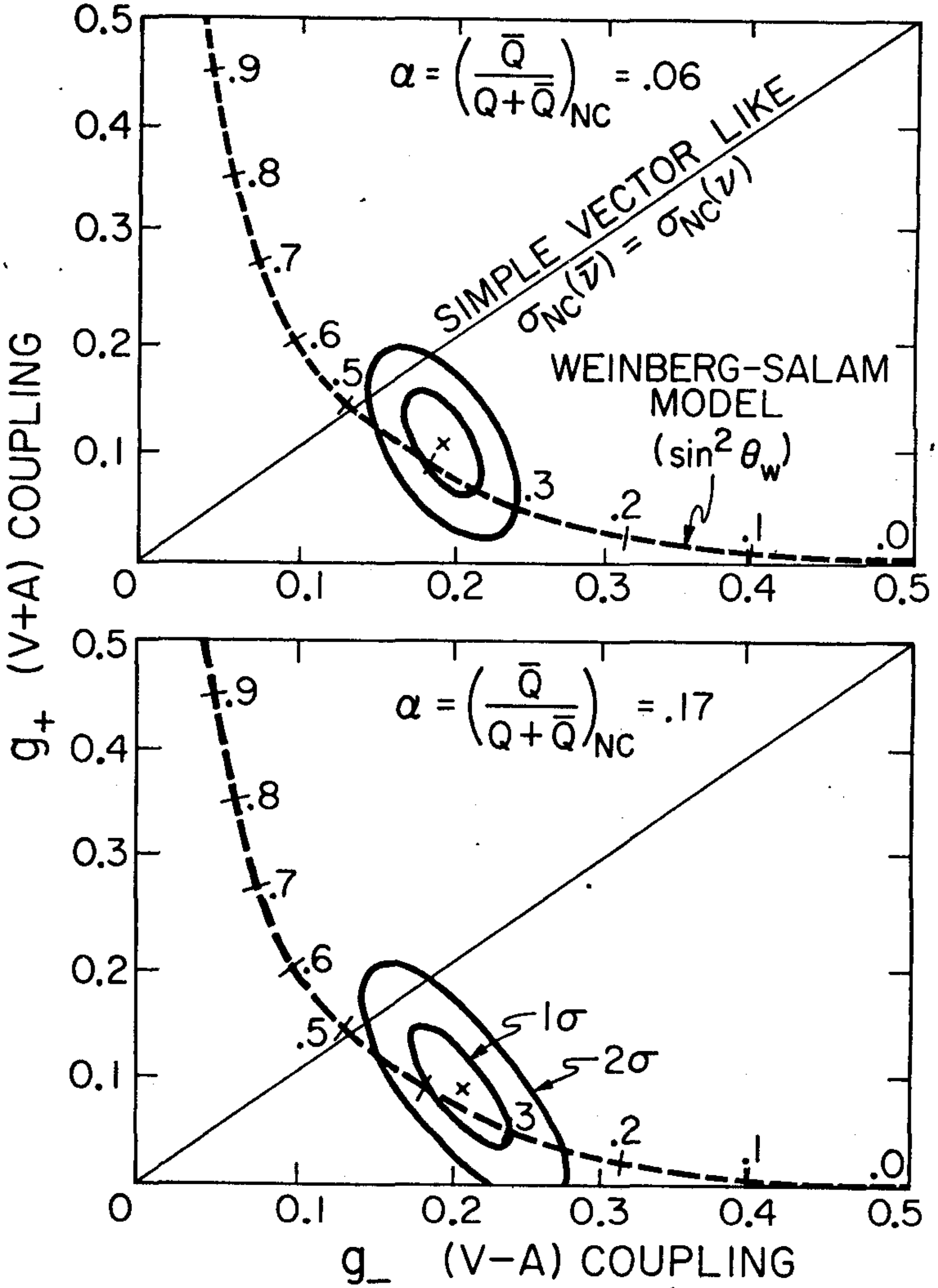


FIG. 7

Two Parameter Contours V-A vs. V+A for $\alpha_{nc} = 0.06$ (7a) and $\alpha_{nc} = 0.17$ (7b). Predictions of the Weinberg-Salam Model and Simple Vector-like Theories Shown for Comparison.